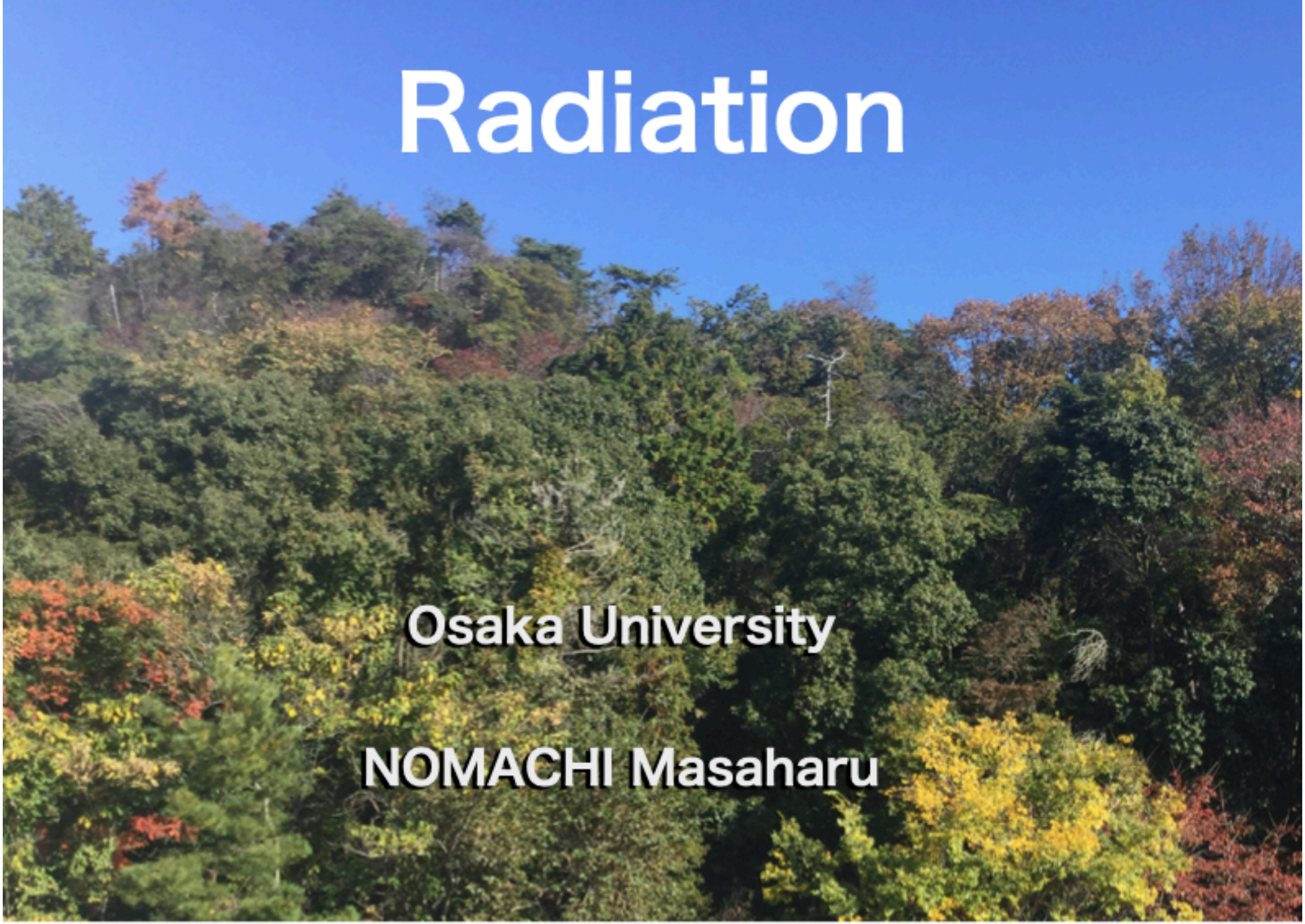


IAEA: Nuclear Medicine Physics: https://www.ene100.jp/map_title_en

Quantized Energy flow

Energy flow is quantized.

Intensity is the number of photon

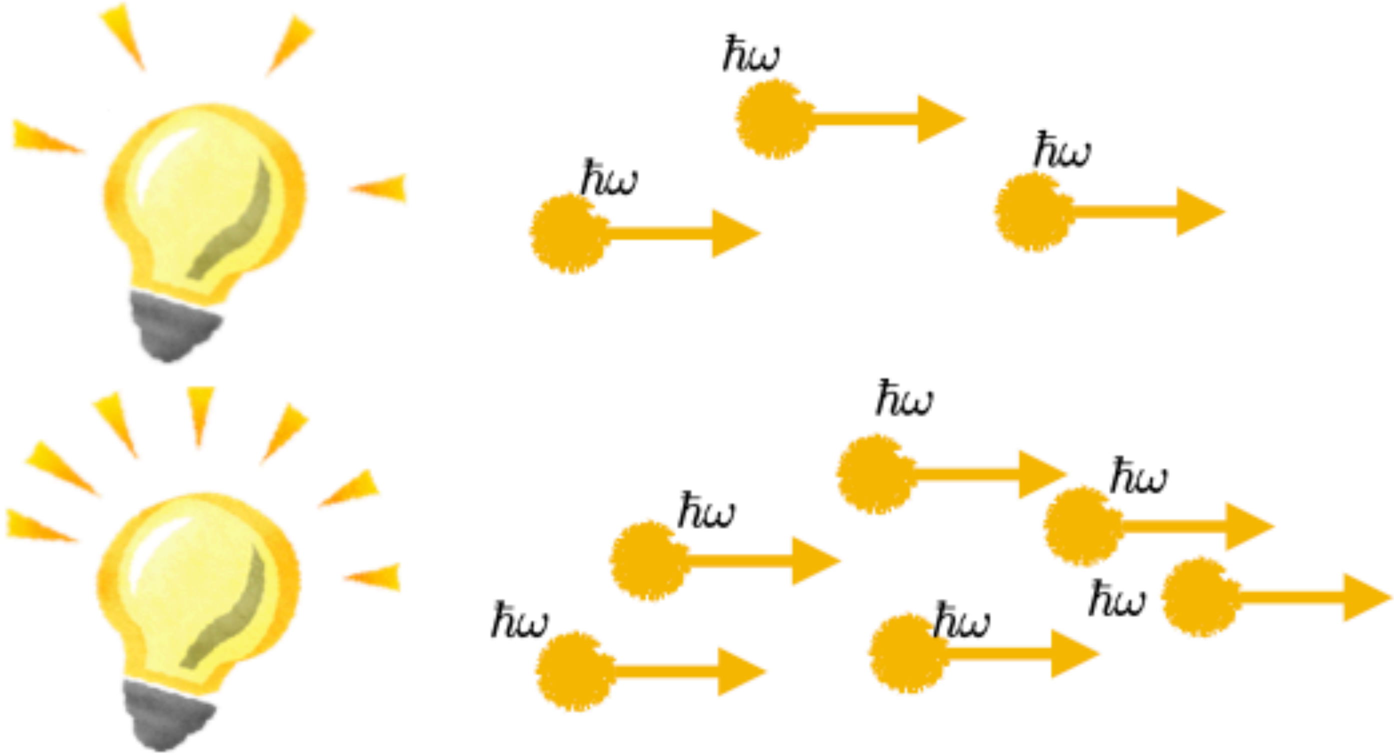


Photo from the Nobel Foundation archive.

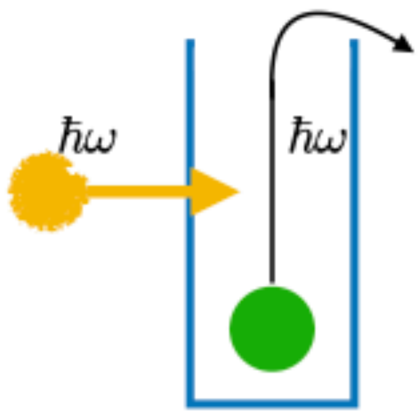
Max Planck

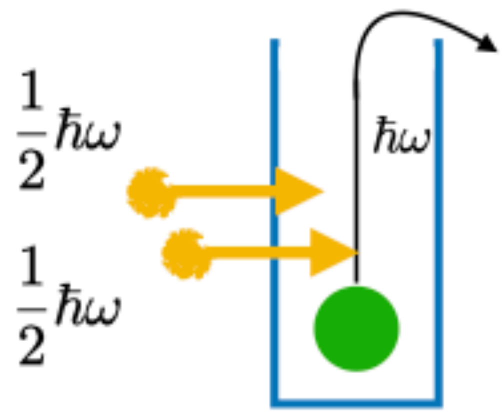
The Nobel Prize in Physics 1918

Prize motivation: "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"

ionization

Energy deposit more than the binding energy is required





Single photon can ionize

Probability is proportional to the number of photon.
(Linear effect $\propto I$)

Single photon cannot ionize

Very high number density is required.
(Non linear effect $\propto I^2$)

High intensity Laser beam allows two photon absorption

Ionizing Radiation =

Each energy quanta has enough energy for ionization.

photoelectric effect

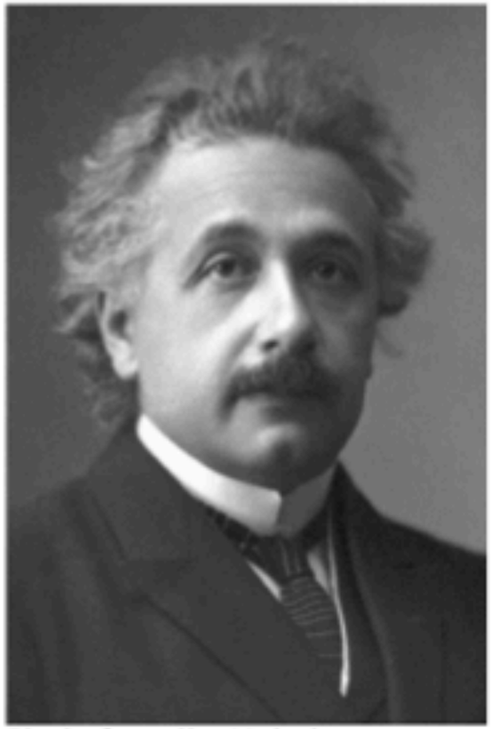


Photo from the Nobel Foundation archive.

Albert Einstein

The Nobel Prize in Physics 1921

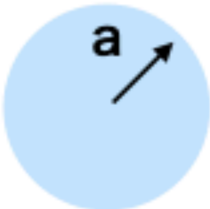
Prize motivation: "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

binding energy

The Feynman Lectures on Physics, Volume I

Chapter 38.The Relation of Wave and Particle Viewpoints **38–4The size of an atom**

The uncertainty principle $\Delta x \Delta p \geq \frac{1}{2}\hbar$



The Kinetic Energy $\frac{p^2}{2m}$ is of the order $\frac{\hbar^2}{2ma^2}$

The Potential Energy is $-\frac{1}{4\pi\epsilon_0}\frac{e^2}{a}$

The Total Energy is $\frac{\hbar^2}{2ma^2} - \frac{1}{4\pi\epsilon_0}\frac{e^2}{a}$ **it is minimum at** $a = \frac{4\pi\epsilon_0\hbar^2}{me^2}$

Fine structure constant $\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137}$

The Total Energy is $-\frac{1}{2}mc^2\alpha^2 =$ -13.6 eV

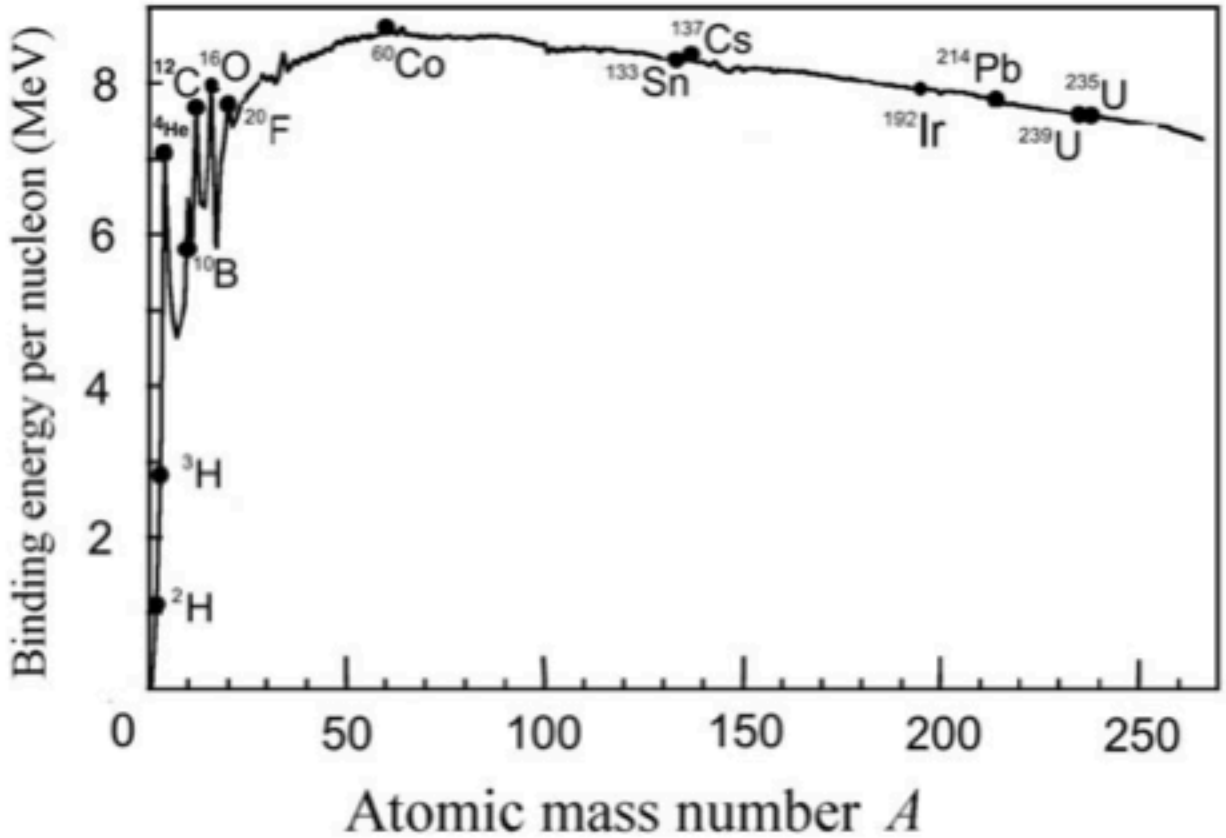


FIG. 1.1. Binding energy per nucleon in megaelectronvolts per nucleon against atomic mass number A. Data are from the National Institute of Science and Technology (NIST).

The Total Energy is $-\frac{1}{2}mc^2\alpha^2 =$ -13.6 eV

Fine structure constant $\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137}$

Nuclear force is
Strong interaction
~ 1
Nucleon is 2000 times heavier

chemical energy

Battery voltage is related to the chemical interactions.

Alkaline manganese battery (1.5V)

$$MnO_2 + H_2O + Zn$$
$$\rightarrow Mn(OH)_2 + ZnO$$

Ni-Cd battery (1.2V)

$$2NiOOH + Cd + 2H_2O$$
$$\rightleftharpoons 2Ni(OH)_2 + Cd(OH)_2$$

Thermal Energy

Energy of gas molecular is proportional to the temperature.

$$E = kT$$

k is Boltzmann constant 8.6171E-5 eV/K

at room temperature, it is about 26 meV = 0.03 eV

It is much lower than the ionization energy

Gravitation

Free fall of 1 kg from 1m high

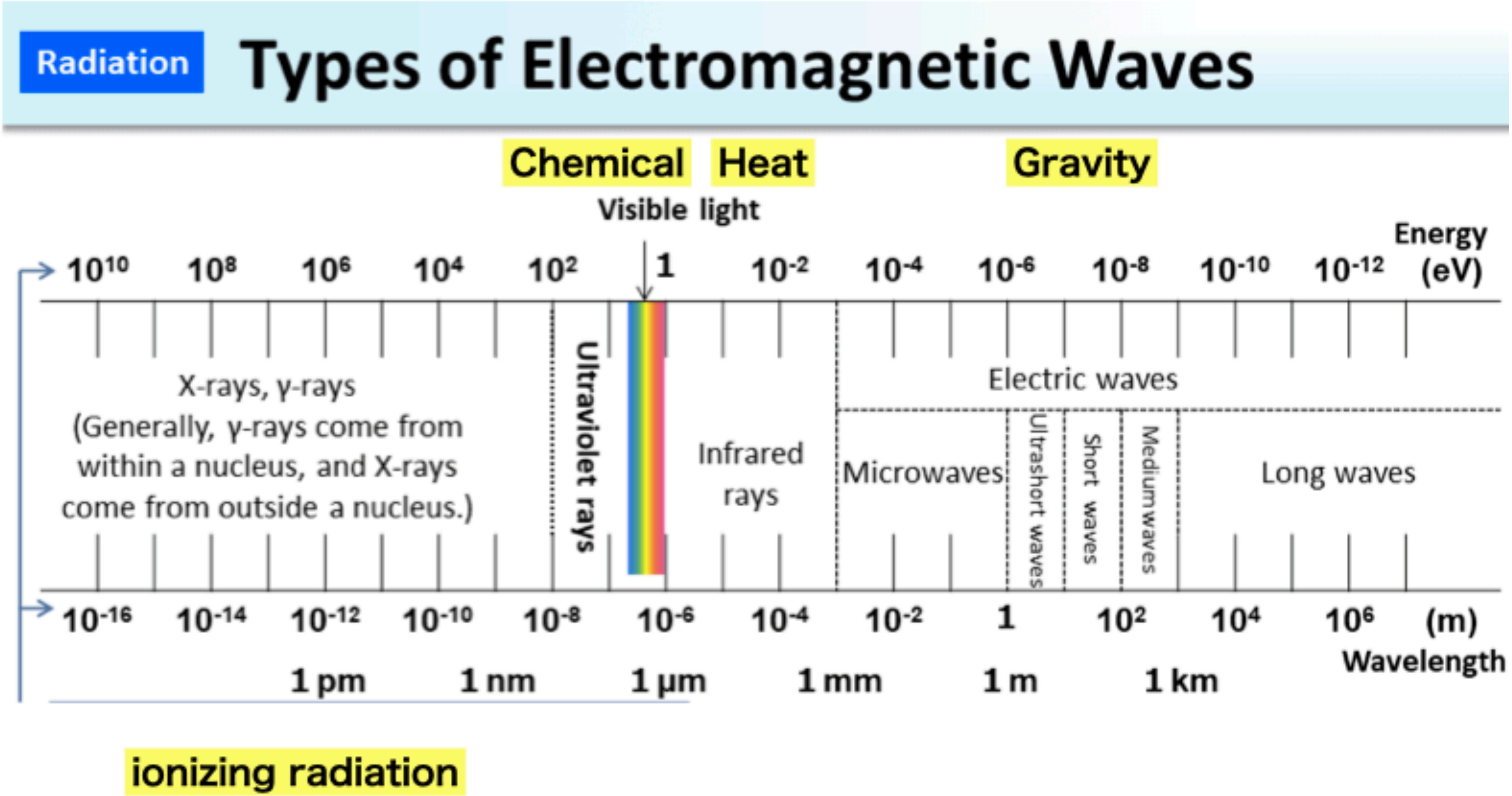
mgh = ~10 J = 6×10^{19} eV

It is large energy but each nucleon may get …

6×10^{19} eV / ($1000 \times 6 \times 10^{23}$) = 1×10^{-7} eV = 100 neV

Compare to other Energy, it is several order smaller.

Energy Scaleionizing radiation



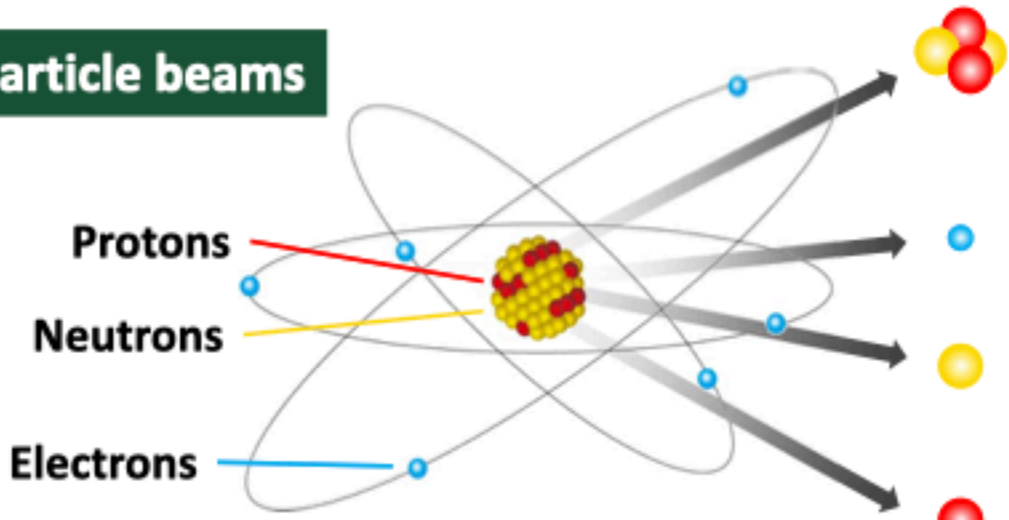
https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

Radiation

Types of Ionizing Radiation

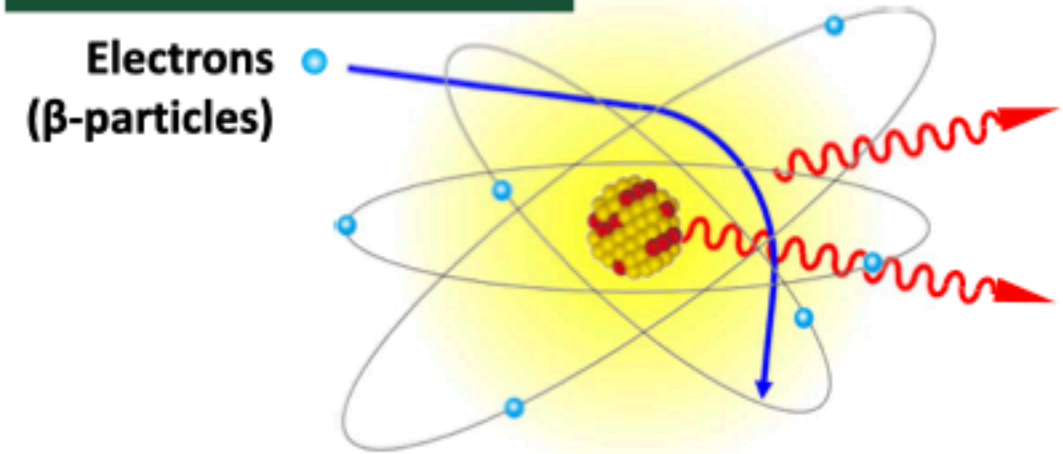
Ionizing radiation — Radiation that causes ionization

Particle beams



- **α-particles** (helium nuclei ejected from a nucleus)
- **β-particles** (electrons ejected from a nucleus)
- **Neutron beams** (produced in nuclear reactors, accelerators, etc.)
- **Proton beams** (produced in accelerators, etc.)

Electromagnetic waves



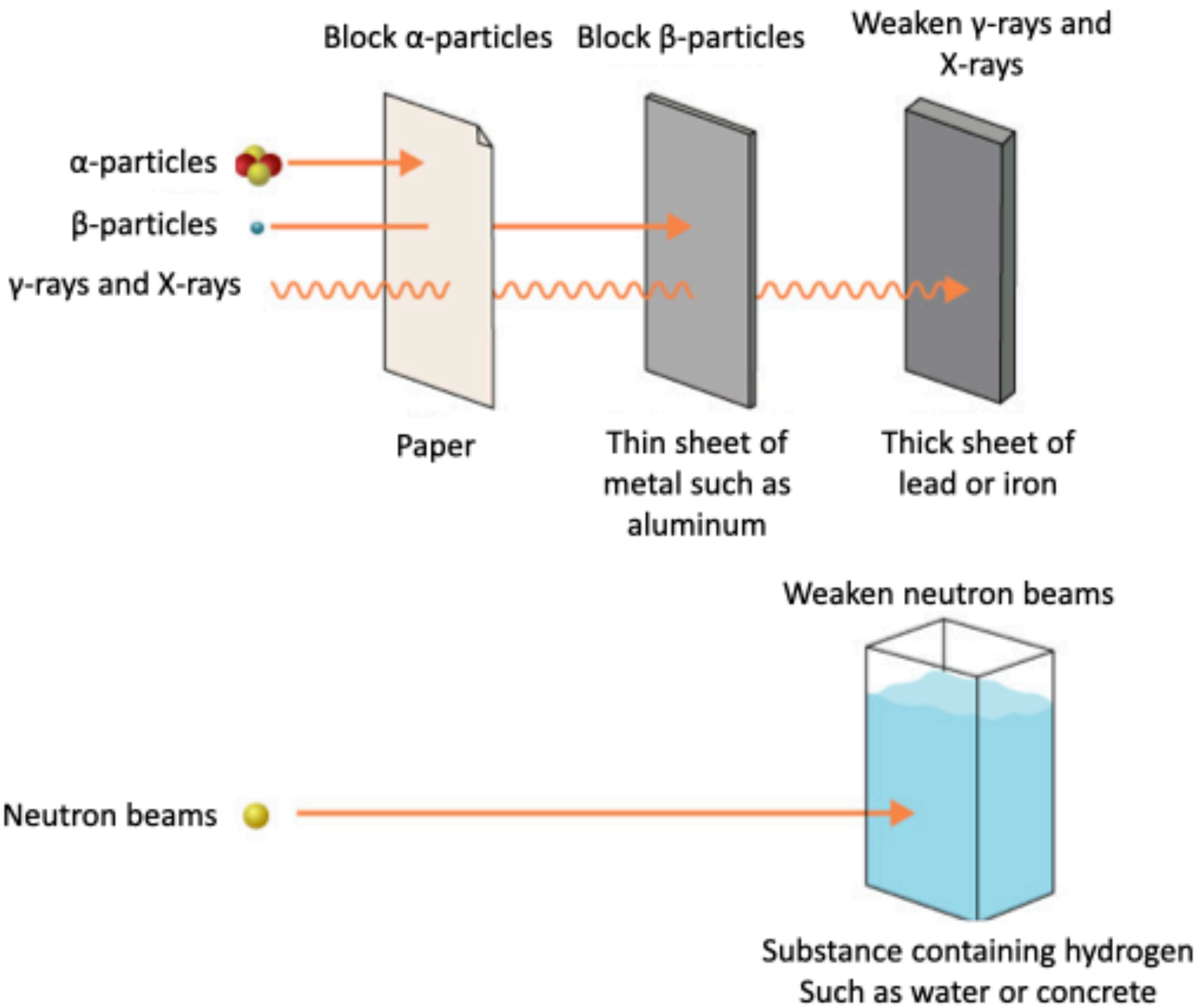
- **X-rays** (generated outside a nucleus)
  - * X-rays generated when electrons within an atom are caused to travel between orbits by incident electrons are called characteristic X-rays.
- **γ-rays** (emitted from a nucleus)

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

Radiation

Penetrating Power of Radiation

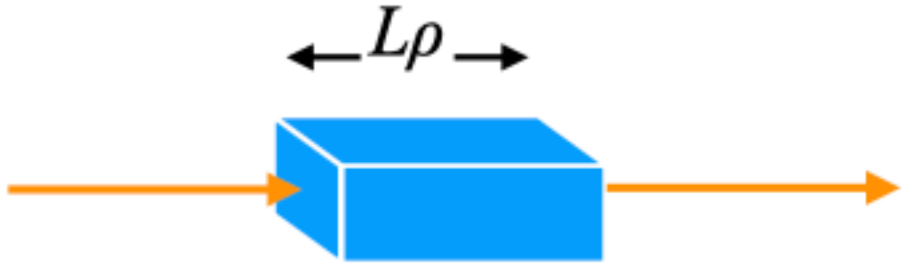
Radiation can be blocked by various substances.



https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

length

The interaction depends on the density.



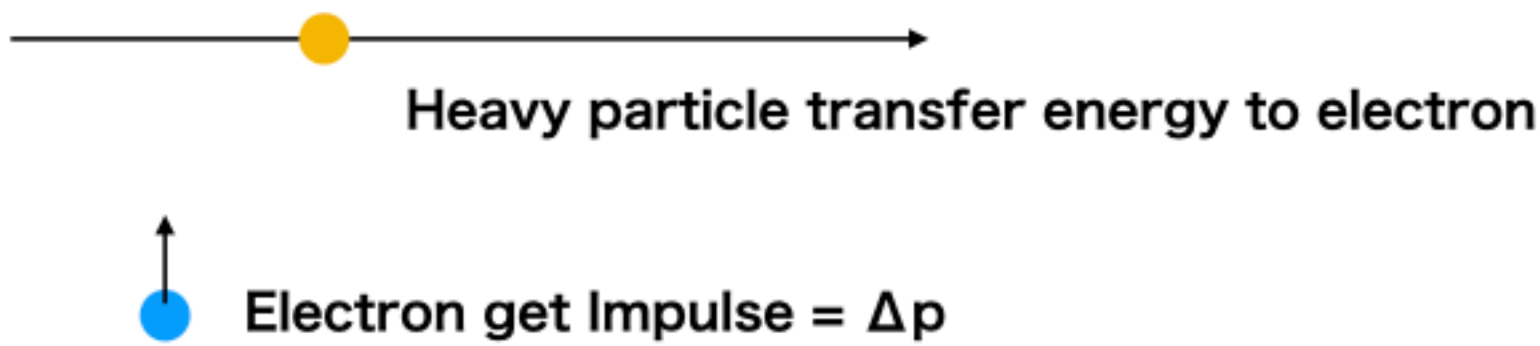
$L\rho$ is proportional to the number of nucleon (~ electron).

Most of radiation effect is described by cm x g/cm^3 = g/cm^2

PASSAGE OF PARTICLES THROUGH MATTER

"Bethe-Bloch" equation,

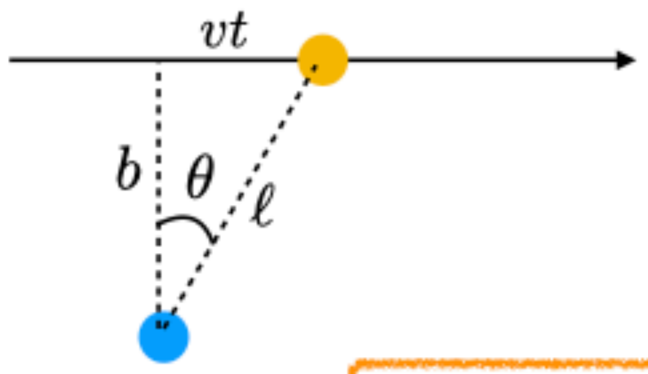
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$



https://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf

$$F = \frac{ze^2}{4\pi\epsilon_0}\frac{1}{\ell^2}$$

$$F_\perp = \frac{ze^2}{4\pi\epsilon_0}\frac{b}{\ell^3}$$



$$\ell\cos\theta = b$$

$$b\tan\theta = vt\,, \quad \frac{bd\theta}{\cos^2\theta} = vdt$$

$$\Delta p = \int F_\perp dt = \frac{ze^2}{4\pi\epsilon_0}\int_{-\infty}^{\infty}\frac{b}{\ell^3}dt$$

$$\int F_\perp dt = \frac{ze^2}{4\pi\epsilon_0}\int_{-\pi/2}^{\pi/2}\frac{\cos^3\theta}{b^2}\frac{bd\theta}{v\cos^2\theta} = \frac{ze^2}{4\pi\epsilon_0}\int_{-\pi/2}^{\pi/2}\frac{\cos\theta}{b}\frac{d\theta}{v} = \frac{ze^2}{2\pi\epsilon_0}\frac{1}{bv}$$

$$\Delta E_e = \frac{\Delta p^2}{2m_e} = \frac{1}{2m_e}\left(\frac{ze^2}{2\pi\epsilon_0}\frac{1}{bv}\right)^2 = \frac{2z^2}{m_ec^2}\left(\frac{e^2}{4\pi\epsilon_0}\frac{1}{\hbar c}\right)^2\frac{(\hbar c)^2}{\beta^2b^2} = \frac{2z^2}{m_ec^2}\alpha^2\frac{(\hbar c)^2}{\beta^2b^2}$$

$$-\left\langle\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right] .$$

Photon Interactions

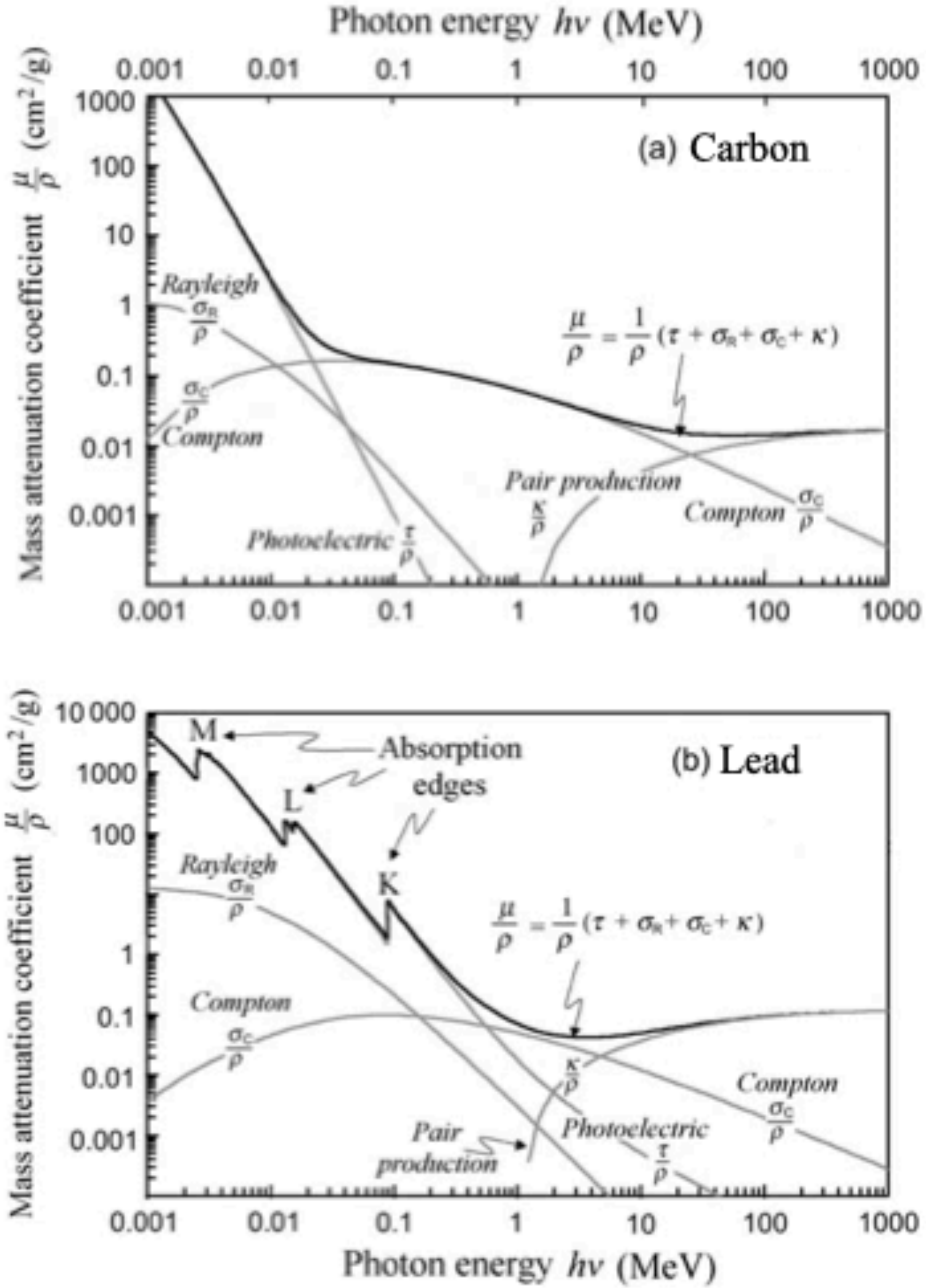
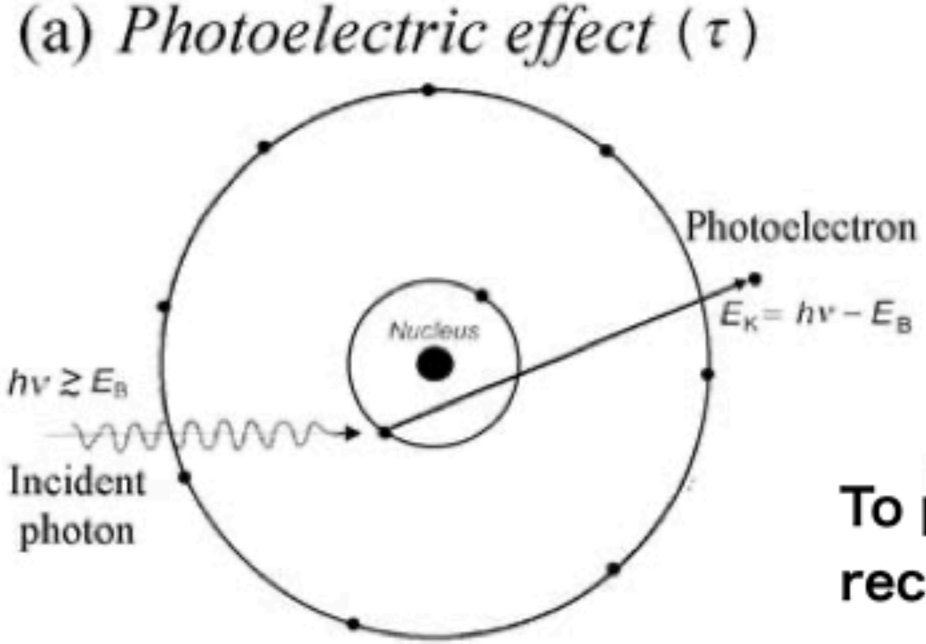


FIG. 1.5. Mass attenuation coefficient μ/ρ against photon energy hν in the range from 1 keV to 1000 MeV for carbon (a) and lead (b). In addition to the total coefficients μ/ρ, the individual coefficients for the photoelectric effect, Rayleigh scattering, Compton scattering and pair production (including triplet production) are also shown. Data are from the National Institute of Science and Technology (NIST).

Photoelectric effect
Compton Scattering
Pair Production

photoelectric effect



To preserve energy and momentum, the recoil of nucleus is needed.

Compton scattering

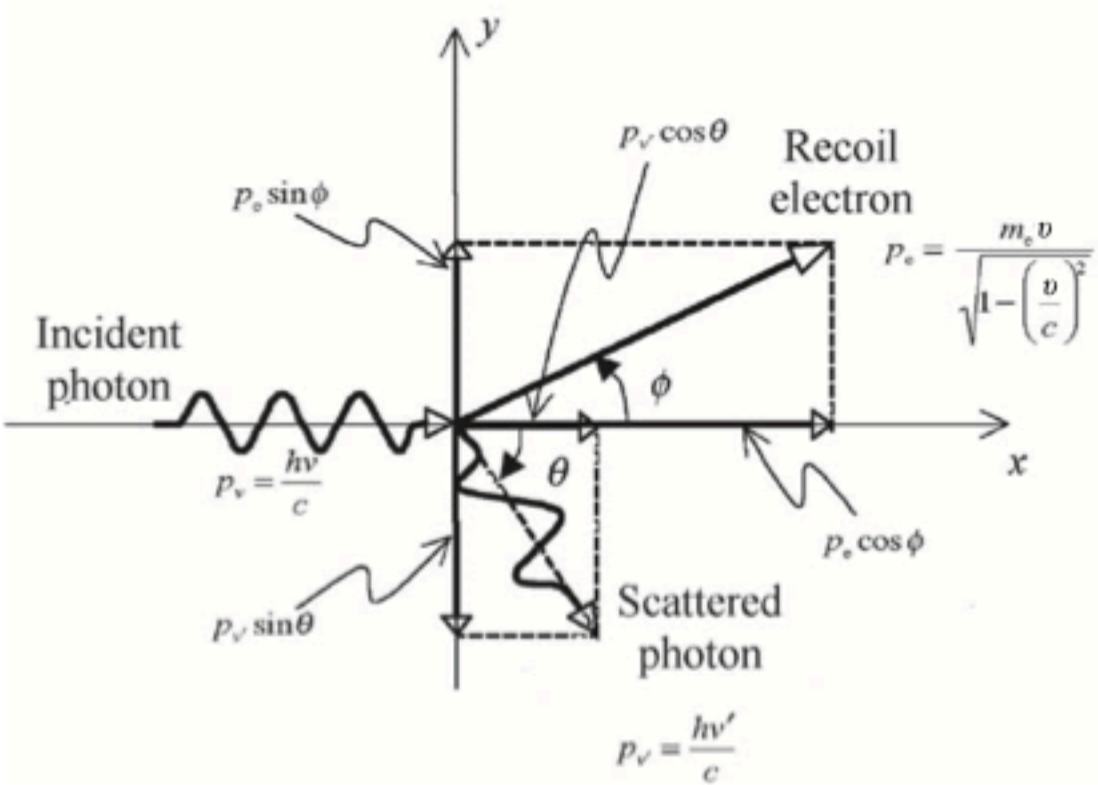
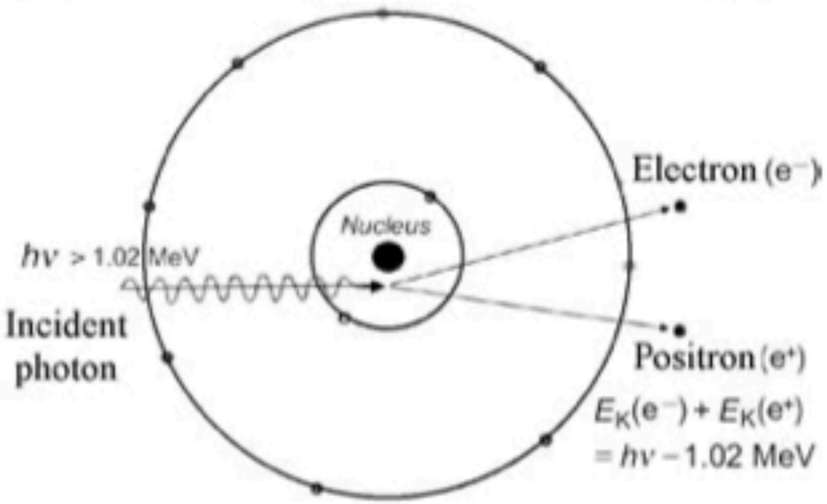


FIG. 1.7. Schematic diagram of the Compton effect in which an incident photon of energy $h\nu$ = 1 MeV interacts with a 'free and stationary' electron. A photon with energy $h\nu'$= 0.505 MeV is produced and scattered with a scattering angle θ = 60°.

Since Compton interaction is a photon interaction with a free electron, the Compton atomic attenuation coefficient depends linearly on the absorber atomic number *Z*

Pair production

(d) Nuclear pair production (κ_N)



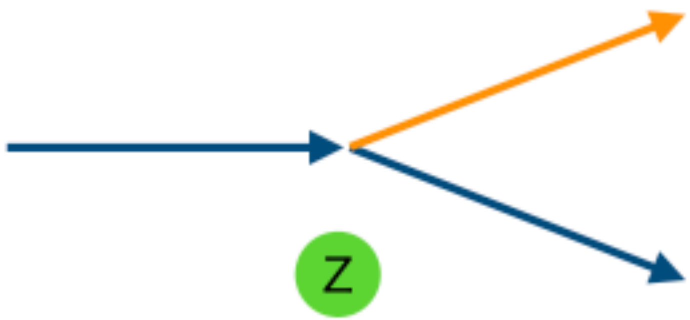
To preserve energy and momentum, the recoil of nucleus is needed.

Photon must energetic more than 2 x electron mass.

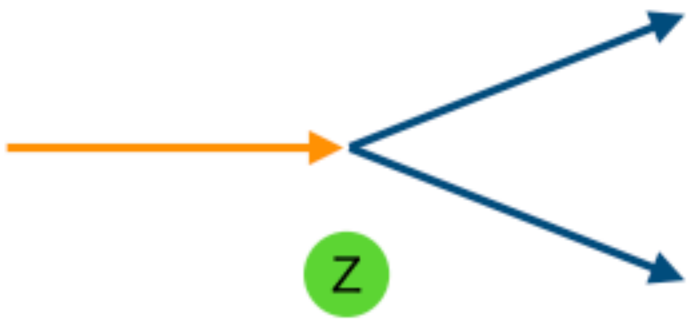
Photon and electron interactions in matter

High-energy electrons predominantly lose energy in
matter by bremsstrahlung, and high-energy photons by e+e– pair production.

bremsstrahlung



pair production



Radiation length

radiation length X_0, usually measured in g cm^{-2}. It is both (a) the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung, and (b) $\frac{7}{9}$ of the mean free path for pair production by a high-energy photon

It causes electromagnetic shower

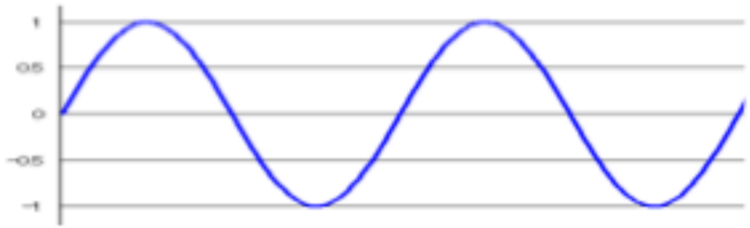
Atomic and Nuclear Properties of Materials

Table 6.1 Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D.E. Groom (2017). See web pages for more detail about entries in this table and for several hundred others. Parentheses in the dE/dx and density columns indicate gases at 20° C and 1 atm. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values ≫1 in brackets indicate $(n-1)\times 10^6$ for gases at 0° C and 1 atm.

Material	Z	A	$\langle Z/A\rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter. length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\|_{min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({g ℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index @ Na D
H_2	1	1.008(7)	0.99212	42.8	52.0	63.05	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.014101764(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.94(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.0121831(5)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.419
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210	Sublimes at 4098. K		
N_2	7	14.007(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.999(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.998403163(6)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815385(7)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.630(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(5)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-atomic-nuclear-prop.pdf

$\hbar c$ = 197 eV nm $\qquad$ $\hbar c$ = 197 MeV fm



1 keV = 1.2 nm （~size of atom)

20MeV = 60 fm （~size of atomic nuclei)

molecule → atomic nucleus

Radioactive Materials

Naturally Occurring or Artificial

Radionuclides	Radiation being emitted	Half-life
Thorium-232 (Th-232)	α, γ	14.1 billion years
Uranium-238 (U-238)	α, γ	4.5 billion years
Potassium-40 (K-40)	β, γ	1.3 billion years
Plutonium-239 (Pu-239)	α, γ	24,000 years
Carbon-14 (C-14)	β	5,730 years
Cesium-137 (Cs-137)	β, γ	30 years
Strontium-90 (Sr-90)	β	29 years
Tritium (H-3)	β	12.3 years
Cesium-134 (Cs-134)	β, γ	2.1 years
Iodine-131 (I-131)	β, γ	8 days
Radon-222 (Rn-222)	α, γ	3.8 days

Artificial radionuclides are shown in red letters.

α: α (alpha) particles, β: β (beta) particles, γ: γ (gamma)-rays

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

Half life

$1 \rightarrow 1/2 \rightarrow 0$

$1 \rightarrow 1/2 \rightarrow 1/4 \rightarrow 1/8 \rightarrow 1/16 \rightarrow 1/32 \rightarrow 1/64$

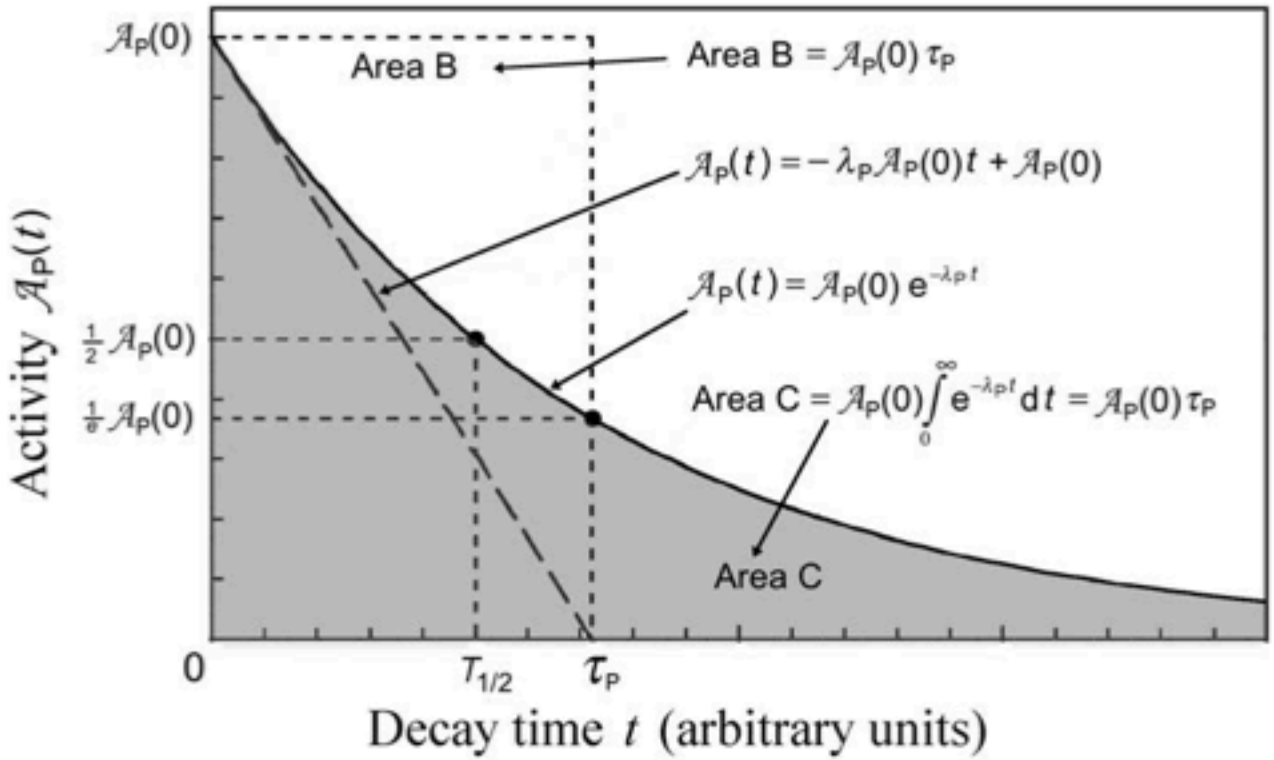


FIG. 1.3. Activity $\mathcal{A}_P(t)$ plotted against time t for a simple decay of a radioactive parent P into a stable or unstable daughter D. The concepts of half-life $(T_{1/2})_P$ and mean life τ_P are also illustrated. The area under the exponential decay curve from $t = 0$ to $t = \infty$ is equal to the product $\mathcal{A}_P(0)\tau_P$ where $\mathcal{A}_P(0)$ is the initial activity of the parent P. The slope of the tangent to the decay curve at $t = 0$ is equal to $\lambda_P\mathcal{A}_P(0)$ and this tangent crosses the abscissa axis at $t = \tau_P$.

Nuclei with Long Half-lives

Example Radioactive materials that had existed in the universe since before the birth of the earth and were taken into the earth upon its birth

Series

A radioactive nucleus repeats disintegration until becoming stable, accompanying changes in nuclides each time.

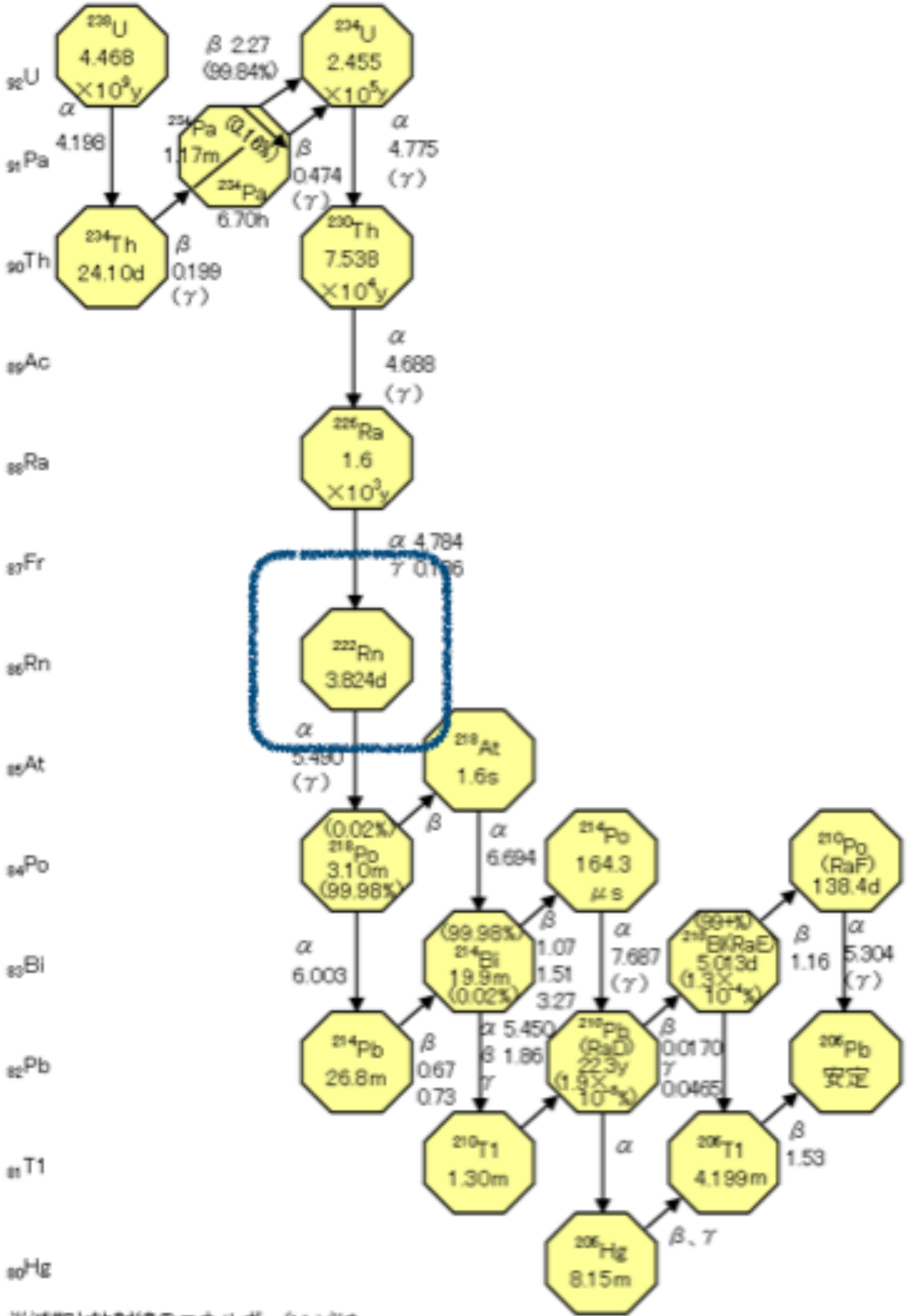
- Uranium-238 (Half-life: 4.5 billion years)
- Thorium-232
- Uranium-235

Non-series

A radioactive nucleus directly disintegrates into a stable nucleus.

- Potassium-40 (Half-life: 1.3 billion years)
- Rubidium-87, etc.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html



半減期と放射線のエネルギー(MeV)は
Evaluated Nuclear Structure Data File(1995年2月)

図2　ウラン(^{238}U)壊変系列

[出典] 日本アイソトープ協会(編):アイソトープ手帳、丸善(2002年7月)、p.13

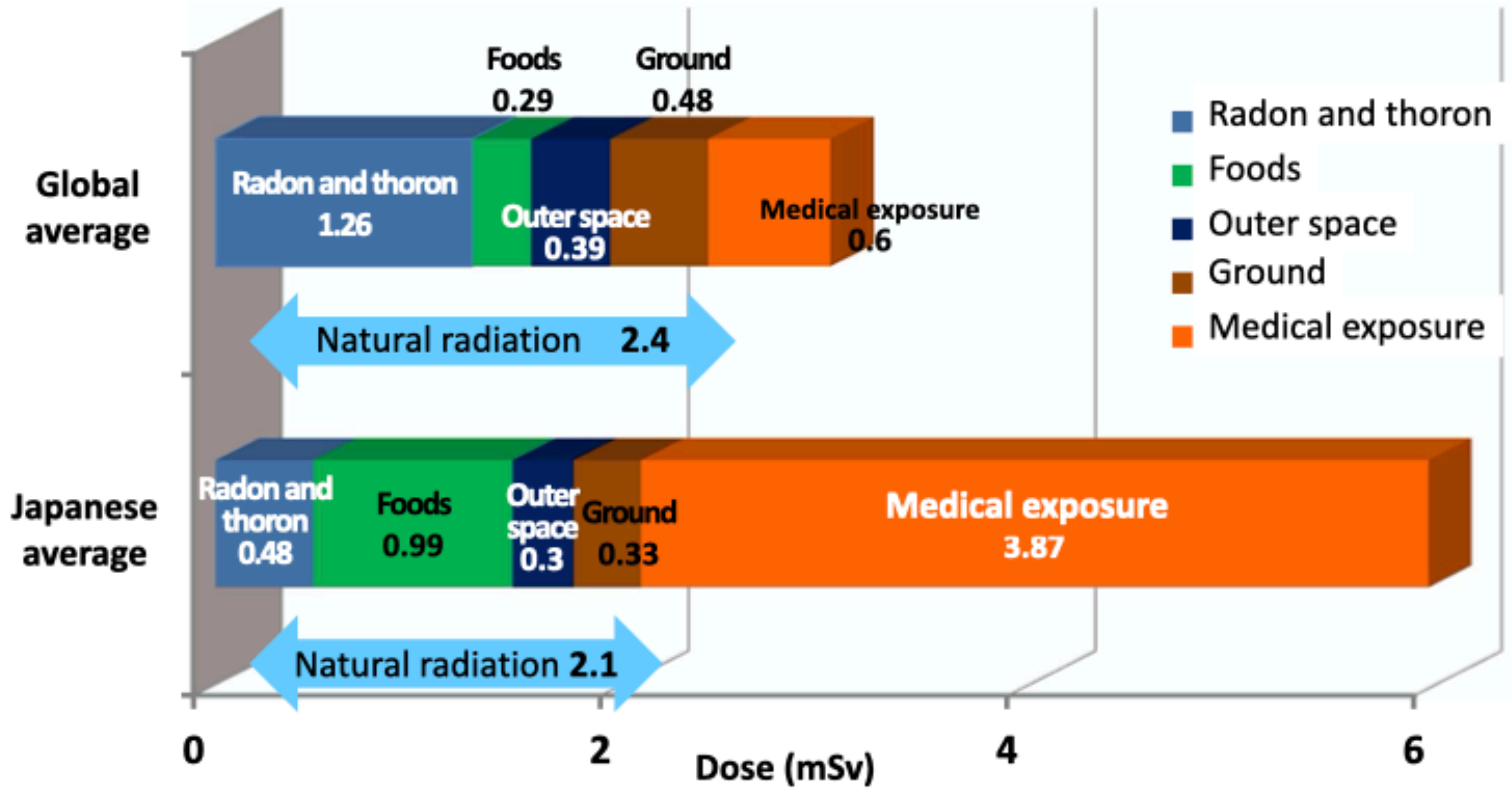
半減期と放射線のエネルギー(MeV)は
Evaluated Nuclear Structure Data File(1995年2月)

図3　トリウム(^{232}Th)壊変系列

[出典] 日本アイソトープ協会(編):アイソトープ手帳、丸善(2002年7月)、p.12

Radiation around Us Comparison of Exposure Doses per Year

Exposure in daily life (annual)



Sources: Prepared based on the 2008 UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) Report; and "Environmental Radiation in Daily Life (2011)," Nuclear Safety Research Association

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

Natural Radioactive Materials in the Body and Foods

Radioactive materials in the body

When body weight is 60kg		
Potassium-40	※1	4,000Bq
Carbon-14	※2	2,500Bq
Rubidium-87	※1	500Bq
Tritium	※2	100Bq
Lead and polonium	※3	20Bq

※1 Nuclides originating from the Earth
※2 Nuclides derived from N-14 originating from cosmic rays
※3 Nuclides of the uranium series originating from the Earth

Radioactivity concentrations (Potassium-40) in foods

Rice: **30**; Milk: **50**; Beef: **100**; Fish: **100**; Dry milk: **200**; Spinach: **200**;
Potato chips: **400**; Green tea: **600**; Dried *shiitake*: **700**; Dried kelp: **2,000** (Bq/kg)

Bq: becquerels Bq/kg: becquerels/kilogram

Source: Prepared based on "Research on Data about Living Environment Radiation (1983)," Nuclear Safety Research Association

Nuclear power plant accidents so far

1979 Three Mile Island Nuclear Accident

1986 Chernobyl nuclear accident

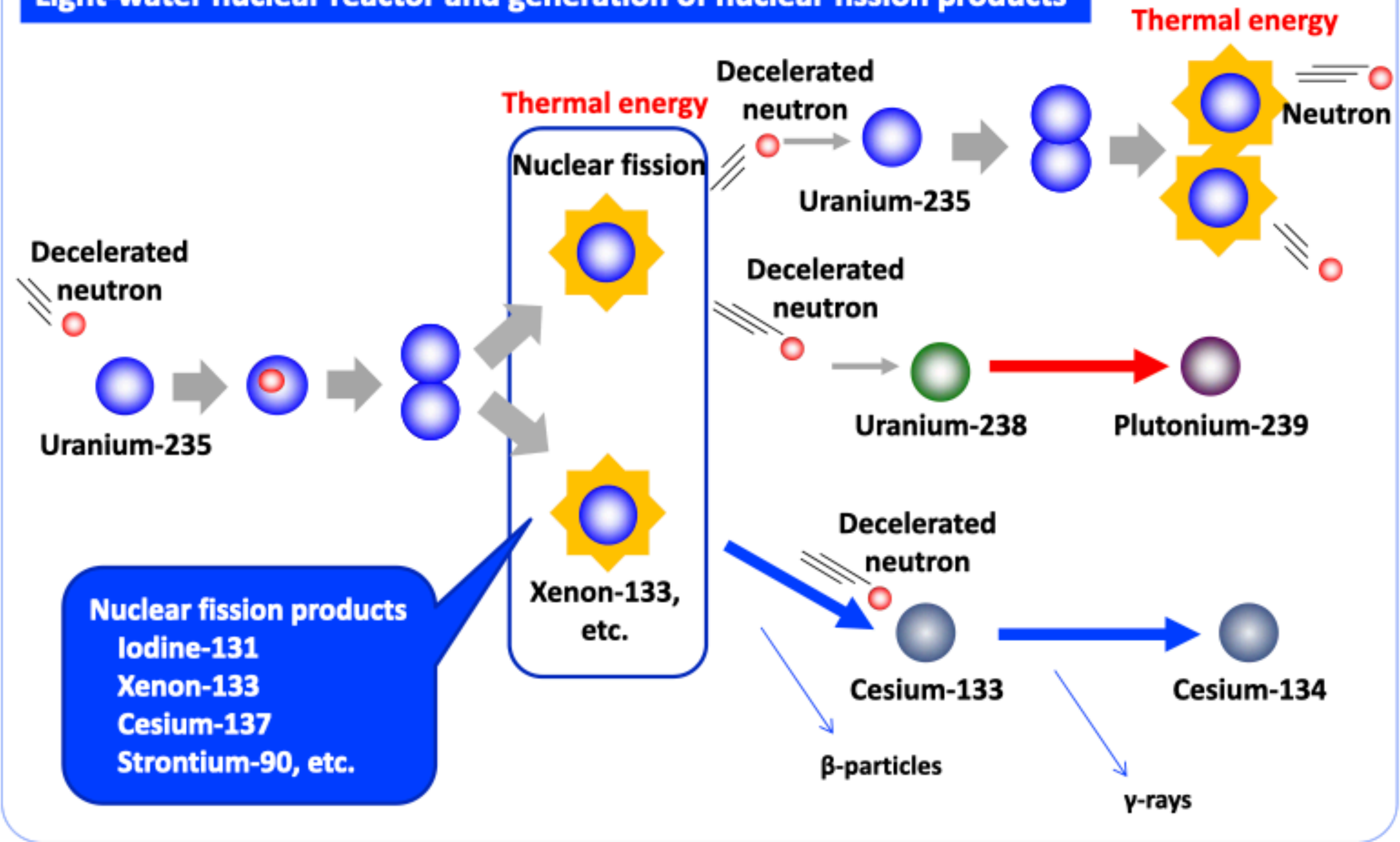
2011 Fukushima Daiichi Nuclear Power Plant Accident

Support for the urgent refugee from the radioactive contamination area

Nuclear Disaster

Products in Nuclear Reactors

Light-water nuclear reactor and generation of nuclear fission products



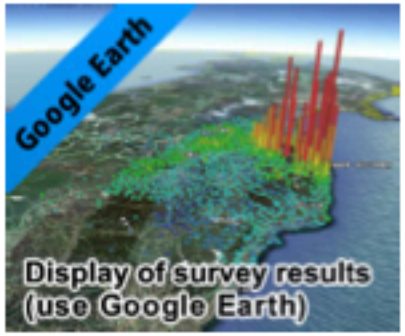
https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

https://www.rcnp.osaka-u.ac.jp/dojo/index_en.php

Survey of Fukushima Soil Radioactivities

～ Radioactivity maps displayed by the Google Earth, Google map ～

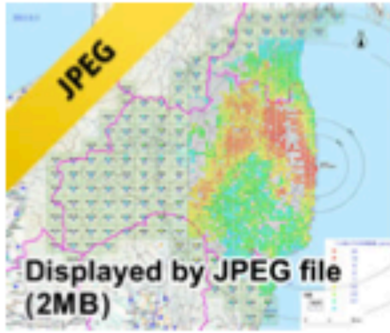
TOP Update About Participants Download



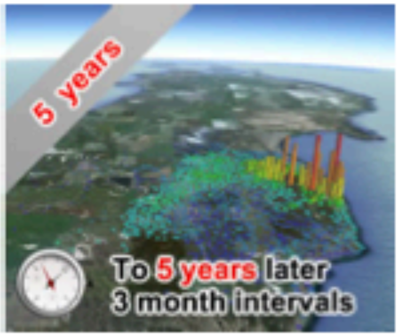
○ High speed PC × Smart phone
× Tablet, Ipad

○ Low speed PC ○ Smart phone
○ Tablet, Ipad

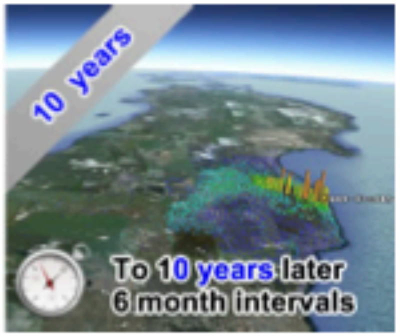
○ Low speed PC ○ Smart phone
○ Tablet, Ipad



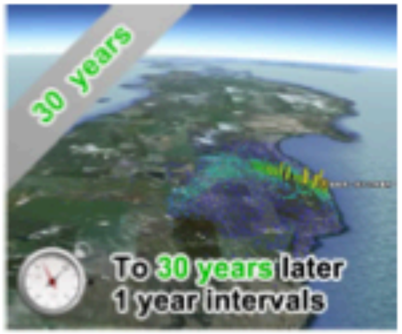
○ Low speed PC ○ Smart phone
○ Tablet, Ipad



○ High speed PC × Smart phone
× Tablet, Ipad



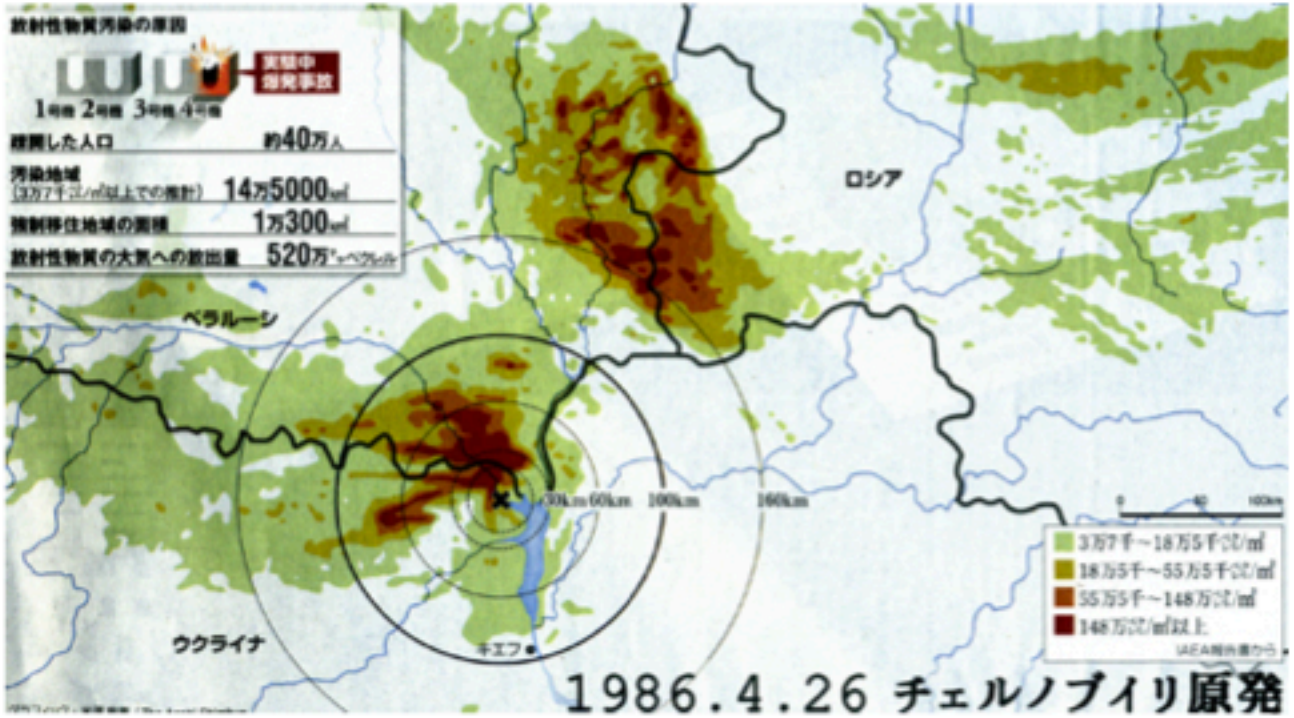
○ High speed PC × Smart phone
× Tablet, Ipad

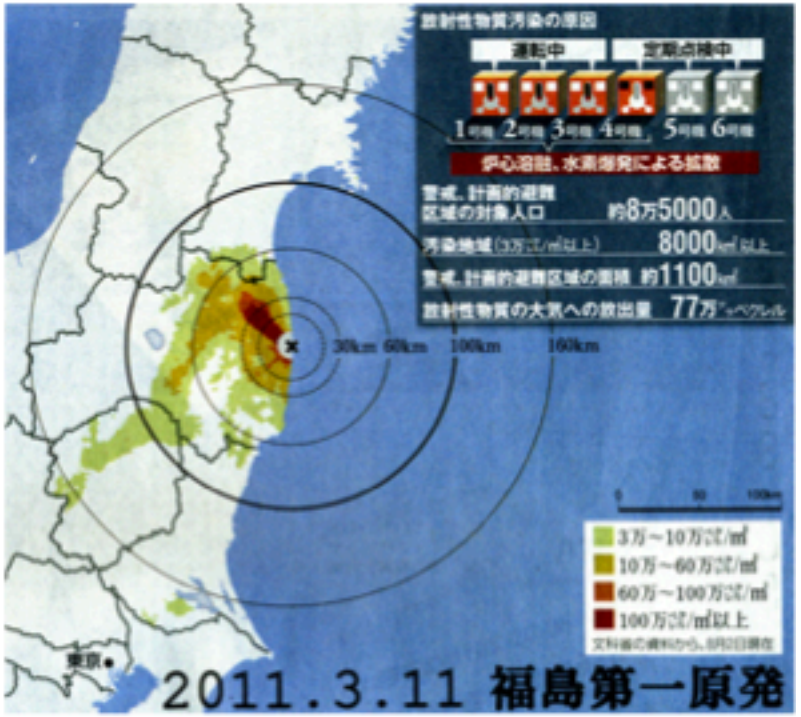


○ High speed PC × Smart phone
× Tablet, Ipad

Comparing the Chernobyl and Fukushima nuclear accidents at the same scale

Accumulation of cesium-137 in soil





（朝日新聞2011.9.11）

18.5万～55.5万Bq/m²	自主移住（希望すれば移住可）区域	10万～60万Bq/m²
55.5万～148万Bq/m²	一次的にしろ移住が必要な区域	60万～100万Bq/m²
148万Bq/m²以上	永久的な移住が必要な区域	100万Bq/m²以上

Decontamination Methods

Decontamination has been conducted in accordance with the circumstances of respective areas.

Specific methods differ by location.

Effective methods differ depending on the status of contamination with radioactive materials. First, ambient dose rates are measured, and an optimal method is selected on a case-by-case basis. Radiation doses are measured before and after decontamination work to confirm the effects.

Measurement → Selection of decontamination methods → Decontamination work → Confirmation of the effects

Case 1 **Decontamination methods employed in areas with relatively low radiation doses**

● The following are examples.

●Cleaning of eaves and gutters of private houses

●Mowing of vegetation (Provided by Date City)

●Removal of sludge from ditches (Provided by Fukushima City)

Case 2 **Decontamination methods employed in areas with relatively high radiation doses** (in addition to the above methods)

●Scraping off of topsoil of school yards (Provided by JAEA)

●Washing of building roofs, etc.

●Scraping off of garden soil, etc. (Provided by Date City)

Prepared based on the website, "Environmental Remediation," of the Ministry of the Environment

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html